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Integrated Assessment of Renewable Energy Potential: Approach and application in rural South Africa

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Abstract

This paper presents the development and application of the Integrated Renewable Energy Potential Assessment (IREPA), employing a three-pronged approach: (i) literature review of renewable energy potential assessment methodologies, renewable energy technology (RET) selection factors and impact assessment methods; (ii) discussions with academic peers from natural and social sciences, and the private energy-engineering sector; (iii) evaluation of the IREPA methodology through case-study research in a rural community in South Africa.

Locally relevant social, institutional, environmental and techno-economic factors were explored through mutual knowledge exchange with smallholders and subsequently applied for appropriate RET selection. Three barriers to participatory decision-making were revealed: i) lack of knowledge of renewable energy among smallholders; ii) insufficient practical information dissemination in IREPA; iii) abstract nature of the analytical hierarchy process.

The adaptions recommended by this research would render IREPA a suitable bottom-up approach for the assessment and effective implementation of RET, stimulating socio-economic development in rural areas.

Key words: Bottom-up; energy’s role in people’s lives; appropriate technology selection; renewable energy implementation potential

Highlights

- Review of methods and factors for assessing renewable energy potentials
- Development of interdisciplinary, participatory, bottom-up approach
- Locally relevant criteria required for appropriate technology selection
- Socio-cultural factors largely determine appropriateness of RE technologies
- Mutual knowledge exchange and education required for RE implementation

1. Introduction

Improving access to clean and modern energy is high on the policy agenda of many developing and emerging economies (Hailu, 2012) and essential to the post-2015 development agenda (UNECOSOC, 2014). Extension of the electricity grid to rural areas where most of the energy-poor households live is technically challenging and often not economically viable due to the low density and dispersed structure of rural settlements (Cherni et al., 2007). Decentralized, renewable energy (RE) systems (solar-, wind-, hydro-, geothermal and bioenergy) can increase access to modern energy in rural areas, (Cherni et al., 2007; Kaygusuz, 2012). By the end of 2015, 146 countries had adopted RE support policies. More than two thirds of these countries are developing countries or emerging economies (REN21, 2016).

The highest technical potential, for solar, wind and biomass energy (about 983 EJ) has been found for the African continent (De Vries et al., 2007). This is almost twice the 2013 total global annual primary energy consumption of 533 EJ (BP, 2014). Currently, modern RE accounts for only 1.5% of the total African primary energy supply, which is based to 51% on fossil fuels and nuclear power and to 47% on solid biofuels such as wood and charcoal (IRENA-DBFZ, 2013).

In South Africa energy is mainly generated from coal (87.5%). Solid biofuels account for 9.4%, while other RE have a share of 1.3% (OECD/IEA, 2016). Since the abolishment of the Apartheid various electrification programmes have been implemented, e.g. *White Paper on Energy Policy (*estd. 1998), *Integrated National Electrification Programme* (estd. 2001) and *Integrated Resource Plan*, (estd. 2011) (DoE SA, 2013). Between 1996 and 2014 5.7 million households were connected to the grid. This transformed the electrification rate in the Transkei (Eastern Cape) from more than 80% un-electrified households in 1996 (DoE SA, 2013) to 82.3% electrified households in 2015 (Stats SA, 2015). For further rural electrification off-grid RET are proposed, in particular in the former homeland areas in KwaZulu Natal and the Eastern Cape, the two provinces with the highest off-grid potential in South Africa (DoE SA, 2013).

Currently, RE development in South Africa is directed by the *Renewable Energy Independent Power Producer Procurement Programme (REI4P*) (DoE SA, 2015). The REI4P is based on a competitive bidding process for RE supply contracts, focusing on large-scale RE-production (> 1MW). In the first three years, the programme has had considerable success. The number of electricity producers has increased from one to 64 and RE electricity prices have decreased. However, the socio-economic development targets of the REI4P, including human capital building as well as job and enterprise creation in rural areas, have not been achieved (Walwyn and Brent, 2015). This shows the limitations of centralized, top-down approaches to reaching remote rural areas and stimulating socio-economic development. In rural areas, RE technologies (RET) planned according to techno-economic considerations by external experts often fail to meet the expectations of a long-term and sustainable energy supply (Hailu, 2012; Wang et al., 2009).

The implementation of RE depends on the complex interaction of social, institutional, environmental, technical and economic factors that determine the adaptability of a technology to the local socio-cultural context (Barry et al., 2011; García and Bartolome, 2010; Kaygusuz, 2012). The involvement of stakeholders is therefore an important condition for successful RE implementation.

Smallholder farmers - defined here as farms with less than 10 ha, often less than 1 ha (Jayne et al., 2010) - manage more than 80% of the natural resources in rural areas (IAASTD, 2009). Therefore smallholders are the stakeholders that should primarily be addressed in RE potential assessments (REPA) and RE implementation programmes in rural areas.

This study presents an innovative methodology to REPA in smallholder farming systems. IREPA was developed with the purpose of integrating the above-mentioned factors in a participatory, bottom-up approach to select locally appropriate RET for the assessment of the renewable energy implementation potential (REIP). For the methodological development, a three-pronged approach was applied. First, current methodologies used for REPA were analysed with emphasis on social, institutional, environmental and techno-economic factors. In addition, appropriate methodologies for participatory research, impact assessment and decision-making were reviewed. Second, the "Integrated Renewable Energy Potential Assessment" (IREPA) was developed based on the results from the previous step, additionally informed by discussions with academic peers and the private energy sector. Third, findings from case-study research in the Eastern Cape Province of South Africa are presented, testing whether IREPA is applicable in this specific context.

2. Methodology

2.1 Development of the IREPA approach

2.1.1 Literature review

Current approaches for REPA were analysed, taking only methodologies into account that assessed the *theoretical*, *geographical*, *technical*, *economic* and *implementation* potential categories as defined by Hoogwijk (2004) and Resch et al. (2008).

In addition, literature on RE case studies was reviewed to explore the social, institutional, environmental, technical and economic factors considered important for RET selection. For the identification of these factors at the local level *Participatory Learning and Action* (PLA)[1] research methods are essential and are therefore included in the literature review (Chambers, 1994; Hart, 2008).

Further, social and environmental impact assessment as well as multi-criteria decision analysis (MCDA) methods were reviewed, drawing on the MCDA reviews of Hailu (2012), Taha and Daim (2013) and Wang et al. (2009), to identify a suitable methodology for assessing the impacts of RET on people's livelihoods and to select locally appropriate RETs in the IREPA.

2.1.2 Discussions with academic peers and the private sector

The results of the literature review were discussed with academic peers from the disciplines agricultural sciences, agricultural economics and social sciences, and with energy engineers from

[1] PLA comprise a wide range of approaches including *Participatory Rural Appraisal (PRA), Rapid Rural Appraisal (RRA), Participatory Learning Methods (PALM), Participatory Action Research (PAR), Farming Systems Research (FSR), and others* (Hart, 2008).

the research and development department on future renewable power technologies of ALSTOM (Schweiz) AG. This enabled an inter- and transdisciplinary research perspective.

2.2 Application and evaluation of IREPA in a rural community in South Africa

2.2.1 IREPA-Methodology

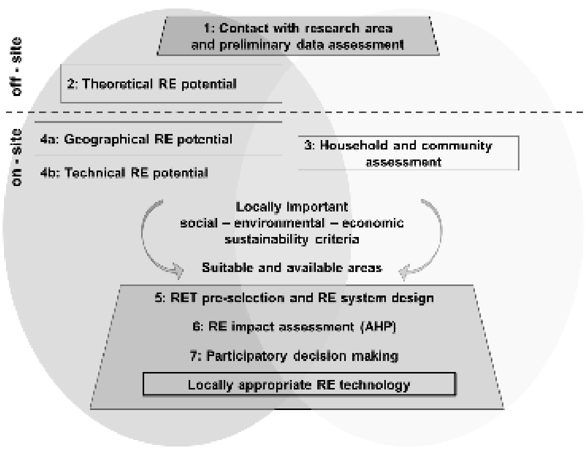


Figure 1: Methodology of the Integrated Renewable

IREPA integrates the techno-economic perspective of energy engineering (trapezoidal box), the bio-physical perspective of natural science (grey circle) for REPA assessment, and the socio-cultural perspective of social science (light grey circle), aiming at applying a participatory, bottom-up approach for appropriate RET selection and REIP assessment (Fig. 1):

Step 1: Contact with Research Area and Preliminary Data Assessment

Contact to the research area and local partners (e.g. local government representatives, research institutions, NGOs, village chiefs, farmers, etc.) is established to engage in a process of information exchange about the local context. For the participatory aspect of IREPA, it is important to have a local contact person in order to gain access to and build up trust with the community where research is conducted (Amigun et al. 2011; Wüstenhagen et al., 2007).

Step 2: Theoretical Renewable Energy Potential (ThREP)

The *ThREP* for solar-, wind-, hydro-, geothermal and bioenergy is assessed according to the REP categories defined by Hoogwijk (2004) and Resch et al. (2008). The bio-physical renewable resource (RR) availability is evaluated by drawing on global and national statistical databases covering the researched area (Tab. 1) as suggested by Angelis-Dimakis et al. (2011).

Renewable Resource	Data Sources
Solar	HelioClim-3 Database of Solar Irradiance
Wind	Wind Atlas for South Africa (WASA)
Hydro	Department of Water and Environmental Affairs (DWEA), South Africa
Biomass	NASA Earth Observations (NEO); Local Biomass Inventory Analysis
Geothermal	Banks and Schäffler, 2006

Name	Affiliation
Luke Boshier	Founder and director of "Centre for Appropriate Rural Technology" (CART)
Dianne van der Walt	Member of CART, Permaculture expert and teacher
Khaya (*surname unknown*)	Project staff of CART
David Philips	Founder and director of "People Empowered Preserved Earth" (PEPE)
Vujani Mgcotyelwa	Member of the Traditional Council of Mgwenyana

Step 3: Household and Community Assessment

For IREPA participatory research methods are applied to assess the household and community characteristics and subsequently identify social, institutional, environmental, technical and economic factors for the selection of locally appropriate RET. For interview design IREPA draws on the *Sustainable Livelihoods Framework* (SLF) (Scoones, 1998), *Environmental Impact Assessment* (Finnveden et al., 2003; UNEP, 2008) and *Social Impact Assessment* (Amezaga et al., 2010) (section 3.3). The following PLA research methods were applied:

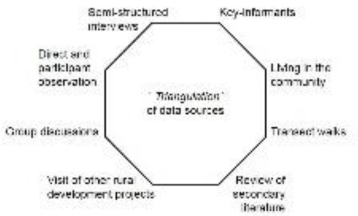
- *Open-ended, semi-structured interviews* with households (n=18, five male, thirteen female) to explore socio-demographic and -economic characteristics as well as perceptions regarding the role of energy in people's lives. The questionnaire was evaluated in a pilot survey with a group of women (n=9) from a nearby agricultural training project who had similar socio-economic characteristics.
- *Key-informant interviews* (n=5) with four development practitioners of CART and PEPE (three male, one female) and one male member of the traditional council of Mgwenyana (Tab. 2).
- *Focus Group Discussions* with above-mentioned key informants, community members participating in the partner organisations' project (two male, fourteen female) and two members of the traditional council (one male, one female).
- *Transect walks* through the community accompanied by *informal interviews* with community members.
- *Direct and participant observation* - field records in the form of written notes, photographs and videos were taken during the interviews, transect walks and while working together with community members in the project.

- *Living in the community* and performing regular daily tasks including fetching water and firewood, preparing food on an open fire and gardening contributed to a better understanding of the community members' daily routine.
- *Visits to four rural development projects* - a former CART project in *Sicambeni* (community about 40 km from Mgwenyana); *Sisonke Eco-school* in Port St. Johns; *Growing the Future* project in Grootbos and *Green Pop* in Cape Town, providing insights into development work in similar settings.
- *Review of secondary sources* including project reports of CART and PEPE.

These PLA methods provided detailed qualitative and quantitative data on local livelihoods. For analysis of qualitative data, the information was transcribed and coded in order to categorize, generalize and interpret it (Creswell, 2009 p. 184ff). The emerging data were cross-checked to obtain reliable data employing triangulation of different data sources (Fig. 2) (Creswell, 2009).

Quantitative data were processed using MSO Excel 2007 performing descriptive statistics. Percentages, averages and ranges were calculated (Creswell, 2009).

The results were structured drawing on the *Sustainable Livelihoods Framework* (SLF) (Scoones, 1998). The tool enables understanding and characterising people's livelihoods with the aim of



retaining factors that determine the role of energy in people's livelihoods. The SLF focuses on people's assets (human, social, physical, natural and financial) and the livelihood strategies adopted to achieve certain livelihood outcomes. Attention is drawn to core influences that shape people's assets: (i) the *Vulnerability Context* describes the external environment that affects the wider availability of assets based on *trends* (e.g. demographics, resource and technology use, etc.), *shocks* (e.g. diseases, natural disasters, etc.) and *seasonality* (e.g. prices, agricultural production, employment etc.) over which people have limited or no control; (ii) *Transforming Structures and Processes* represent institutions, organisations, policies and legislation that influence livelihoods from a household to international level and from private to public spheres, and that determine access e.g. to decision-making bodies and capital (including terms of exchange between different types of capital) and returns (economic or otherwise) from any livelihood strategy (DFID, 1999).

The emerging data were compared with RET selection factors derived from the literature (section 3.2). Subsequently, the ten most important factors were selected based on the frequency with which a factor was mentioned in the household and key-informant interviews. These factors reflect the aims and requirements to be met by a RET for it to be appropriate in a particular local context, and are regarded as *local RET sustainability criteria*.

Furthermore, in this step special emphasis is placed on the assessment of suitable and available biomass resources (including land for energy crops) for energy production. In addition, the system boundary (spatial extension of the community) is defined.

Step 4a: Geographical Renewable Energy Potential (GREP)

Bio-physical data on RRs within the system boundary (incl. temporal patterns) are employed to assess suitable areas for RE generation. For this purpose local power densities are evaluated based on threshold values for technical utilisation (Tab. 3). RR with power densities below the threshold values are excluded from the assessment. The bioenergy potential is assessed in a biomass inventory analysis. This is based on the exploration available biomass resources (agricultural residues, organic kitchen waste, animal and human excreta, etc.), performed in step 3.

Step 4b: Technical Renewable Energy Potential (TREP)

From the suitable areas identified, those areas available for RE generation are selected according to the local RET sustainability criteria. The conversion efficiencies of locally available RET are also included to assess the TREP.

Step 5: RET Pre-selection and Energy System Design

Suitable RET are pre-selected based on the *TREP* and the local RET sustainability criteria. RET options are pre-selected and planned by the researchers considering the availability of required materials and technology devices including their prices. For planning the whole RE generation value chain is considered by drawing on LCA's cradle-to-grave perspective (Keam and McCormick, 2008).

Step 6: Energy System Impact Assessment

Local appropriateness of the proposed RETs is assessed by considering the impacts on the daily life of household members and on the environment. To select the most appropriate RET, the *Analytical Hierarchy Process* (AHP) is applied (Saaty, 1990). In the AHP, each proposed RET is evaluated using quantitative and qualitative selection criteria. First, the local RET sustainability criteria are arranged in pairs. Local participants rate the importance of the two criteria based on a scale of 1 to 9, where 1 indicates equal importance and 9 absolute importance over the other. Second, each participant compares the proposed RETs, arranged in pairs with each other, and with respect to each sustainability criterion. The pair comparisons allow the computation of a decision matrix. Based on participant ratings, the eigenvector of (i) each sustainability criterion and (ii) of each RET is calculated using matrix algebra. The eigenvector expresses the priority of each participant (Saaty, 1990).

Finally, two rankings are obtained. The first states the importance of each sustainability criterion. The second reveals the most appropriate RET, either at community level, when taking all participant rankings into account, or at household level, when taking an individual ranking into account.

Step 7: Participatory decision-making process

Finally, the AHP ranking is presented to the households and/or community in a *Focus Group Discussion*. The expenses and requirements for the achievement of individual benefits associated with a particular RET are considered by calculating *benefit:cost*, *benefit:labour* and *benefit:land area* ratios (Saaty, 1990). With full information at hand, local participants can ideally take the final decision for one or a combination of RETs.

2.2.2 Case study area

IREPA was applied in the rural community of Mgwenyana (31°55’ S; 29°23’ E) in the Eastern Cape province of South Africa from August to December 2012. Mgwenyana consists of four villages with a total of 9568 inhabitants in 736 homesteads. The four villages - *Masemeni*, *Kunduna*, *Mahkuzani* and *Mputshane* - cover an area of about 12.75 km² along the hillsides of the *Mngazi River* valley from 207 to 395 meters above sea level. The climate is subtropical with a mean annual temperature of about 18-19 °C (Moyo et al., 2010). Average annual precipitation is 735 mm, characterised by a distinct rainy and dry season (DWEA, 2012).

Research was conducted in cooperation with the non-governmental organisations *Centre for Appropriate Rural Technology* (CART) and *People Empowered Preserved Earth* (PEPE). CART was approached by the traditional leaders to assist the community in utilizing their assets and natural resources in a sustainable way. Community development initiated by the local chief family provides a very suitable setting for applying the bottom-up IREPA.

2.2.3 Monitoring and Evaluation

Monitoring and evaluation (M&E) of the IREPA methodology took place continually throughout the application in field research, according to the guideline of the *Monitoring and Evaluation in Energy for Development International Working Group* (M&EED IWG 2006). For each IREPA step a causal chain was established that links the required inputs (e.g. permission to stay in and research the community) to the activity undertaken (e.g. application of PLA methods) and to the outputs (e.g. factors concerning the role of energy in people's lives), allowing for an evaluation of whether the expected outputs of each IREPA step had been achieved. If an IREPA step is not applied successfully, this M&E approach provides information on the area of failure, e.g. a missing input or the inapplicability of an applied method to achieve the expected output.

3. Results

The first section presents the results of the thematic literature reviews and discussions with academic peers and the private sector, which led to the development of IREPA. The second section provides insights from IREPA case study research.

3.1. Renewable energy potential assessment methodologies

The assessment of the *theoretical, geographical, technical, economic* and *implementation potential* is based on the factors summarized in Table 3.

The *theoretical* and *geographical potential* depends primarily on the bio-physical RR availability at a given location (incl. annual patterns), as well as environmental (land cover) and technical factors (minimum power density for technically utilization). These factors determine the power density on the ground and in turn the areas suitable for harnessing these resources (Hoogwijk, 2004).

Numerous studies assessed the global *technical potential*, exploring the suitability and availability of areas for RE generation (Campbell et al., 2008; Cho, 2010; Field et al., 2008; Goldemberg et al., 2000; Haberl et al., 2011; Lightfoot and Green, 2002; Moriarty and Honnery, 2012; Sims et al., 2007; Smeets et al., 2007; Tomabechi, 2010; WEC, 2010; Wolf et al., 2003). This assessment depends on

Table 3: Brief overview of social, institutional,

REP category [a]	Definition [a]	Determining factors	Description of factors
Theoretical	Physical renewable resource availability	*Bio-physical*	Climatic, geographical and geological conditions in the research area (Hoogwijk, 2004; Resch et al., 2008)
Geographical	Suitable areas for harnessing renewable resources	*Bio-physical, technical*	Power density: - e.g. Solar power density: > 120 W m^{-2} on ground (Hoogwijk, 2004) - e.g. Average wind speed: > 4 m s^{-1} at 10 m height (Kumar et al.,2010) - e.g. Average wind power density: > 400 W m^{-2} at 30 m height (De Vries et al., 2007) Occurance of surface water and height gradient (Resch et al., 2008) Biomass as scarce resource in semi-arid and arid areas (water = limiting factor) (Smeets et al., 2007) Areas with geothermal sources and drilling depth (Resch et al., 2008)
		Environmental	Incompatible land cover (Hoogwijk, 2004, De Vries et al., 2007)
Technical	Availability of suitable areas	*Social*	Current land-use patterns (Smeets et al., 2007) Social acceptance of RE - (lack of) knowledge about RE (Hoogwijk, 2004)
		Social, environmental, economic, institutional	Competition with other land and resource uses (Moriarty and Honnery, 2012), espically for bioenergy (Smeets et al., 2007)
		Environmental, technical	Accessibility (Smeets et al., 2007) and available infrastructure (Moriarty and Honnery, 2012)
		Institutional	RE policy support (Resch et al., 2008)
	Technical conversion efficiency	*Technical, economic, environmental, social*	Type and characteristics of selected RET (De Vries et al., 2007)
Economical	Investment costs Energy production costs Interest rate	*Institutional, social, economic*	Public and private investments/procurement (Gross et al., 2003) RE policy support (Resch et al., 2008) and fiscal incentives e.g. feed-in-tariffs, tax exemptions, and others; RE portfolio standards (Gross et al., 2003)
Implementation	***Social, institutional, environmental, technical and economic factors***		

a complex interaction of environmental, technical, institutional and social factors including: accessibility (Smeets et al., 2007); existing infrastructure (Moriarty and Honnery, 2012); energy transmission/transportation/storage (Sims et al., 2007); current land use (Smeets et al., 2007); and acceptance and willingness of individual land owners to produce RE (Hoogwijk, 2004). RET-specific environmental and social constraints have been summarized by Moriarty and Honnery (2012) and include: resettlement and adverse effects on biodiversity due to inundation (hydropower); noise, vibration pollution, visual appearance and bird death (wind energy); competition for resources (e.g. fertile land and water) and between biomass uses (food, feed, fibre, fuel) (bioenergy). Additionally, the conversion efficiency as well as operation and maintenance (O&M) requirements are considered (Hoogwijk, 2004).

Three studies explored the *economic potential* (De Vries et al., 2007; Gross et al., 2003; Hoogwijk, 2004), considering factors such as specific investment costs (De Vries et al., 2007), energy generation costs (Gross et al., 2003) and interest rates (Hoogwijk, 2004).

The reviewed REP studies apply large spatial resolutions (e.g. grid cell size of 0.5° latitude x 0.5° longitude; Hoogwijk, 2004; De Vries et al., 2007). Suitable and available land areas are assessed based on assumptions, average values and trends (De Vries et al., 2007; Hoogwijk, 2004; Lightfood and Green, 2002; Moriarty and Honnery, 2012). According to the *World Energy Council* (WEC, 2010) these averages and trends are often based on studies conducted at a specific area and at some point in the distant past. Hoogwijk (2004) and De Vries et al. (2007) found in sensitivity analyses of their REPA studies, that personal and social values have a profound influence on the availability of suitable areas. Hence, it is likely that extrapolation of such data to country, regional and global level yields inaccurate results.

Only one study assessed the *implementation (realizable) potential* for the year 2020. Social and institutional factors have been revealed as major barriers to RE implementation and the authors concluded that effective policies are needed (e.g. REI4P in South Africa) to overcome these barriers (Resch et al., 2008).

Amigun et al. (2011) obtained insights into the perspectives of rural communities in the Eastern Cape Province on a planned, large-scale bioenergy project. The authors concluded that conflicts between national and local interests may arise when RE development decisions are made without consulting local communities. The landscape in the former homelands of South Africa is dominated by smallholder subsistence farming. Complex historical processes have resulted in multiple land administration schemes controlled by traditional leaders, government institutions and farmer associations, with varying power division, impacting on land tenure and access to natural resources (Hamann and Tuinder, 2012). Hence, perspectives of multiple individuals need to be considered.

To achieve socio-economic development in rural areas, the REI4P established stringent guidelines on RE project ownership, fostering the inclusion of previously disadvantaged groups: 40% South African entity participation, 12-20% black ownership (Black Economic Empowerment, BEE) and at least 2.5% local community shareholding (Baker, 2015). However, the competitive bidding process is centralized and tailored to large-scale projects to cover the increasing energy demand with RR (Pollet et al., 2015). Consequently, RE generation is concentrated among a small number of companies, as in the South African coal mining sector (Baker, 2015). The bidding consortiums are formally led by national companies and supported (financially) by international partners (Walwyn and

Brent, 2015). Compliance with BEE and the focus on socio-economic community development is sometimes problematic to communicate to foreign companies and investors (Baker, 2015).

Thus it is questionable whether this top-down, centralized policy, favouring the lowest RE generation costs, is capable of including local stakeholders' interests to achieve the associated development aims.

All reviewed REPA methods apply a top-down approach, not or only partly considering local stakeholders' perspectives. Several authors have argued that RE-project planning and implementation requires a holistic approach to planning and action through interactive and effective communication, public participation from the beginning, and pooled learning among the relevant stakeholders to directly benefit rural communities (Amigun et al., 2011; Brent and Kruger, 2009; Ejigu, 2008).

In IREPA, the structure of defined potential categories was adopted to assess the REIP. IREPA shifts from centralized, top-down planning and the extrapolation of average values and trends to a bottom-up assessment of the social, institutional, environmental, technical and economic factors at local level to account for local diversity.

3.2. Selection factors for appropriate renewable energy technologies and role of energy in people's lives

The local appropriateness of a RET depends on a variety of factors (Barry et al., 2011). Figure 3 summarizes RET selection factors based on the literature. In REPA studies *key* or *major* RET of high importance on RE market and with electricity as energy output (Gross et al., 2003; Hoogwijk, 2004; Resch et al., 2008) are most frequently used as reference technologies (e.g. a 1MW wind turbine with 69m hub height; De Vries et al., 2007). Suitable areas are assessed based on the specific requirements of the reference turbine on the wind power density. For example only areas with at least 400 W m^{-2} at 30 m height are considered suitable (De Vries et al., 2007).

Technical, economic and environmental factors include technological efficiency, investment and operation costs as well as the kind and degree of environmental pollution, and are mainly quantitative. Institutional factors include general regulations for RET implementation (e.g. legislation, policies, strategies, agencies), public awareness raising, market promotion, technical capacity building, health and safety measures, enforcement of environmental protection laws and funds or subsidies including tax reduction/exemption and partnerships with donor agencies (Barry et al., 2011).

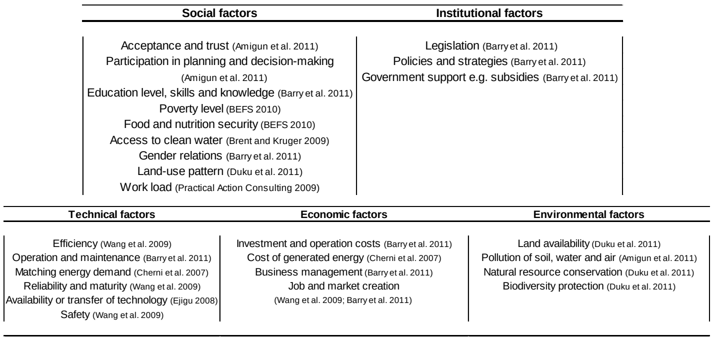


Figure 3: Important factors for the selection of appropriate

Whether a new technology is implemented and operated successfully in the long term depends on its acceptance (Amigun et al., 2011; Hailu, 2012). Acceptance is based on considerations such as information distribution, particular benefits, individual capacity of households and ability to meet their energy needs (Barry et al., 2011; Eijgu, 2008) and further on socio-cultural aspects such as current land-use patterns (Duku et al., 2011); gender relations, e.g. work distribution; food security (BEFS, 2010) and access to clean water (Brent and Kruger, 2009). In the *Survey of energy related behaviour and perception in South Africa* (DoE SA, 2012), the Eastern Cape citizens designated *keep electricity prices low* (76%), *reduced load shedding and power cuts* (60%), and *free electricity and help for poor households* (55%) as top priorities for government action.

Technology is a social construct and inextricably linked with individual behaviour, the latter often being the reason for technical failures e.g. repeated failure of electric connections or poor location of PV panels (García and Bartolomé, 2010; Schäfer et al., 2011). Additionally, people are not rational decision makers. There is a discrepancy between the material needs that people state and their actual behaviour (Frederiks et al., 2015). Knowledge and skills transfer, adapted to the local context

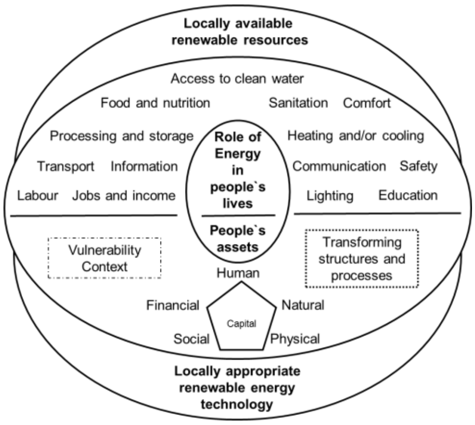


Figure 4: A bottom-up approach for the selection of locally appropriate RETs based on locally available resources,

is deemed important for technology acceptance (Barry et al. 2011). For example, replacing traditional indoor fireplaces with electric stoves significantly reduces indoor air pollution, related impacts on users' health and the risk of compartment fires (WHO, 2008). However, during case-study research it was found that smoke helps to keep mosquitoes and rodents out of the houses, thus protecting against insect-borne diseases and aiding food storage. Soot particles help seal thatched roofs.

Emphasising the role of energy in people’s lives requires an exploration of local socio-cultural aspects, (García and Bartolomé, 2010) and livelihood assets including available construction materials and technology parts (Fig. 4).

The SLF was adopted for IREPA to understand and holistically characterise the livelihoods of smallholder farming households (Tab. 4) (DFID, 1999). For example, the SLF was applied for planning small-scale bioenergy projects (Vargas, 2010), for impact analysis of foreign technologies on local livelihoods (Henao, 2012) and for selecting appropriate energy systems in rural areas (Cherni et al, 2007). In IREPA the SLF allows for consideration of the wider impacts coming along with the substitution of energy sources and for identification of local RET sustainability criteria.

Table 4: Summary of reviewed methods and tools for data acquisition, analysis and impact assessment including

Method / Tool	Scale of application	Stakeholder participation	Sustainability dimensions	Use for IREPA	Source
Participatory Learning and Action Research Methods (PLA)	Small to large scale	Yes	Human, social, institutional, environmental, physical, economic	Participatory data and information acqusition methods	Chambers, 1994; Hart, 2008
Sustainable Livelihoods Framework (SLF)	Small to large scale	Yes	Human, social, institutional, environmental, physical, economic	Holistic characterisation and understanding of local livelihoods based on assets; data structuring	DFID, 1999; Scoones, 1998
Life-Cycle Assessment (LCA)	(Small) to large scale	No	Environmental (economic)	Cradle-to-grave perspective for planning RET options	Finnveden et al., 2003; Keam and McCormick, 2008
Bioenergy and Food Security (BEFS)	(Small) to large scale	No	Techno-economic, environmental, socio-economic	Modular assessment structure	BEFS, 2010
Environmental Impact Assessment (EIA)	Large scale	(Yes)	Environmental socio-economic socio-cultural	Socio-economic/-cultural factors for planning RET options	Finnveden et al., 2003; UNEP, 2008
Strategic Environmental Assessment (SEA)	Large scale	Yes	Environmental (socio-economic)	Strategy of defining goal and evalute options by using criteria	Alshuwaikhat, 2005; Finnveden et al. 2003
Social Impact Assessment (SIA)	Small to large scale	Yes	Socio-political	Bottom-up approach; social factors; stakeholder consultation,	Amezaga et al., 2010; Dutta and Bandyopadhyay, 2010

3.3. Participatory impact assessment methods

Participatory impact assessment methods were reviewed and integrated for IREPA to consider the impacts a RET may has on local livelihoods (Tab. 4).

Participatory Learning and Action Research Methods are useful for community characterisation (see section 2.2.1).

IREPA was informed by *Life-Cycle Assessment (LCA)* for the planning of RETs as it considers the resource and environmental aspects of the production, use and disposal of commodities based on the “cradle-to-grave” perspective (Finnveden et al., 2003; Keam and McCormick, 2008).

IREPA further retains the interdisciplinary assessment structure of the FAO’s *Bioenergy and Food Security (BEFS) analytical framework*, consisting of a natural resource assessment paired with an analysis of the techno-economic, environmental and socio-economic background at country level to support policymakers in formulating bioenergy policies (BEFS, 2010).

IREPA further draws on elements of *Environmental Impact Assessment (EIA)* and *Strategic Environmental Assessment (SEA)* for exploring the impact of RETs on local livelihoods, with a focus on socio-economic and socio-cultural factors. This includes, among others, land use; resource management; community structure; employment; distribution of income; goods and services; local customs and attitudes (Alshuwaikhat, 2005; Finnveden et al., 2003; UNEP, 2008).

Lastly, IREPA integrates selected aspects of *Social Impact Assessment (SIA).* For exploration of household and community characteristics, socio-political variables are adopted, including: population characteristics; community and institutional structures; political and social resources; individual and family changes; and community resources (Amezaga et al., 2010). In SIA stakeholder participation in the project implementation process aids decision-makers to understand the consequences of their decisions before actions are taken (Dutta and Bandyopadhyay, 2010).

3.4. Participatory selection of appropriate renewable energy technologies

Nowadays single criteria approaches that focus on the identification of the most efficient technology with the lowest costs are being replaced by Multi-Criteria-Decision Analysis (MCDA) methods (Wang et al. 2009). MCDA considers a wide range of quantitative and qualitative factors and individuals' perspectives. Technology options and selection criteria are identified and subsequently ranked by participants to reach a decision. The most frequently used MCDA method in sustainable energy decision-making is the *Analytical Hierarchy Process* (AHP) (Taha and Daim, 2013; Wang et al., 2009). This descriptive method allows stakeholders (e.g. smallholder farmers) to compare and rank a set of selection criteria and technology options (arranged in pairs) to identify the most appropriate technology (Saaty, 1990). For example, an adapted AHP was applied to determine suitable RETs in Istanbul (Kaya and Kahraman, 2010) and to select the most appropriate "solar-PV home system" in rural Bangladesh (Ahammed and Azeem, 2013). The AHP was adopted for IREPA with the aim of allowing the local population to select appropriate RET.

3.5. IREPA - Application in a rural community in the Eastern Cape province of South Africa

Access to the community (IREPA-step 1) was established through the existing link to the NGO from previous research carried out by an author of this paper (S.L.). This allowed two authors of this paper (B.W., J.R.) to live in Mgwenyana for one month. Research was facilitated through the close relationship between the NGO and the local chief, who had approached the NGO to assist with finding sustainable solutions for the integrated use of energy that would also enhance food security. The ThREP (IREPA-step 2), expressed as local power densities of the respective RR, indicates potential for solar, wind, hydropower and bioenergy at the study area (Tab. 5), while no geothermal energy potential exists (Banks and Schäffler, 2006).

PLA methods (IREPA-step 3) revealed that the majority of households in Mgwenyana (86%) practice low-input, subsistence farming, while 94% rely on social grants for their income. It was therefore concluded that RE implementation should foster job and income creation.

	Solar	Wind	Hydro	Geothermal	Biomass
	[$W\ m^{-2}$]	[$W\ m^{-2}$]	[W]	[W]	[$W\ m^{-2}$]
Average	**186**	**14** [a]	**16721** [c]	**0**	**1.1**
Seasonality	110 - 256	14 - 33 [b]	2785 - 45972	0	1.06 - 1.17
Source	Helio-Clim 3	WASA	DWEA	Banks and Schäffler, 2006	NEO

a - roughness class 2; 10 m hub height (mainly

All households visited experience a lack of food and dietary diversity, especially at the end of the month, and contaminated water supplies. Thus the authors suggest that RE production should support local food production, processing and storage e.g. by providing energy for pumping water for irrigation, running agricultural machinery, using a fridge or introducing the concept of nutrient recycling from organic residues and wastes along with the implementation of biodigesters.

While all households are connected to the grid (average household electricity demand: 0.96 kWh d^{-1}), firewood is the main energy source. Sufficient electricity is unaffordable for most households. Hence, RETs with low energy generation costs or with higher resource-use efficiency are favourable in this case.

Daily activities are strictly divided by gender: women do all household chores, including fetching wood and water, while men make decisions regarding household resources and generate income. However, 55% of households are de facto female-headed, with male partners having migrated for work, and with only 20% of them supporting the household financially. This results in women being responsible for the livelihoods of their family, often struggling in a male-dominated society. Women will be operators and maintainers of a RET. Thus it is beneficial if information dissemination, RE planning and technical training is addressed at women.

An important social aspect to consider in RET selection is *mona* (*Xhosa* - "jealousy"), imposing that every community member should have the same level of wealth, which is similar to the more popular *Xhosa* term *Ubuntu* ("I am because we are"). While this moral obligation supports social networks and caring for each other, on the other hand it poses barriers to pursue individual initiatives. *Mona* implies that a collective RE project, e.g. a mini hydropower station at the *Mngazi River* operated and maintained by a small group of engaged community members, is likely to be suppressed. The remaining community members may not buy the hydroelectricity in order to not enrich the members of the collective. Therefore, and due to the low power density of the river during dry season (Tab. 5), hydropower was excluded from further assessment. *Mona* further implies that all households should benefit equally, e.g. by RET implementation at each household or by receiving the same amount of funding for RET.

All households fall under the traditional leadership of the chief family. Individual or communal actions, entrepreneurial plans, land and resource use, relations to other communities and (personal) conflicts are discussed at regular community meetings and decisions, e.g. about RET implementation, are taken collectively. Subsequent RET implementation needs guidance by the chief family to avoid tensions within the community (*mona)*.

Research further revealed that community members observe changes in weather and seasonal patterns. They are aware about environmental changes, manifested as direct impact on agricultural activities e.g. irrigation needs because of lower precipitation. This may serve as motivation for transforming towards environmentally sound energy sources.

The above community characteristics were analysed with regard to their social, institutional, economic, environmental and technical relevance for RET selection and were then transcribed into local RET sustainability criteria (Tab. 6).

The suitability of local RR was evaluated based on threshold values (IREPA-step 4a). The annual average solar irradiance (186 W m^{-2}; Helio-Clim-3, 2012) is very suitable for energy generation, with a local power density far above the threshold value of 120 W m^{-2} (Hoogwijk, 2004). The biomass inventory analysis identified grass from field clearance (currently burned before planting crops), organic kitchen waste as well as cow, goat, chicken and human excreta as suitable resources for biogas production. The aggregation of these resources results in an average biogas potential of 5.5 kW per household and day. Wind energy was excluded from the assessment. The annual average wind speed at Mgwenyana was found to be 1.19 m s^{-1} at 10 m height (WASA, 2012) (Tab. 5). This is far below the threshold value of 4 m s^{-1} at 10 m height, necessary for wind power generation (Kumar et al., 2010).

For the TREP the suitability and availability of areas in the community was explored (IREPA-step 4b). For solar panels, north-, east- and west-facing roof areas (63.6 m² per household) are

Table 6: Ranked sustainability criteria based on the

Ranked sustainability criteria	Averaged eigenvector
1. Access to clean water	0.2234
2. Protection of soil, water, air and biodiversity	0.1961
3. Food and nutrition security	0.1782
4. Gender aspects	0.0991
5. Social cohesion and stability	0.0746
6. Social benefits and increased well-being	0.0652
7. Operation and maintenance (local resources)	0.0603
8. Investment costs	0.0366
9. Creation of "green jobs", new products/markets	0.0349
10. Energy security / reliability	0.0315

Table 7: Renewable Energy Technologies considered

Averaged Eigenvector	Ranked RE systems (according to eigenvector)	Normalized costs [ZAR per homestead]	Benefit : Cost ratio
0.2115	Integrated Terrace System	0.0341	6.1928
0.1167	Rocket stove	0.0100	11.6237
0.1154	Solar water heater coil	0.0075	15.3266
0.1098	Biodigester	0.3515	0.3123
0.0966	Solar geyser	0.5355	0.1805
0.0775	Photovoltaic light system	0.0613	1.2649

considered suitable and are currently un-used. Installing PV-panels on the roofs requires no occupation of land areas potentially useable for food production. Combining the roof areas of all 736 households, the annual average of 2343 sunshine hours (Durban Climatetemps, 2012) and the conversion efficiency of locally available amorphous solar panels (10.1%; Green et al., 2010) indicates a technical solar electricity potential of 2805 kWh per household and year.

The GREP of biomass multiplied by the average efficiency of biogas stoves (63.5%; Rajendran et al., 2012) provides a technical biogas potential of 1279 kWh per household and year for cooking.

In IREPA-step 5 suitable RET options were pre-selected by the authors (B.W., J.R.) and the key-informants considering local RR, RET sustainability criteria and available construction materials and technical devices (Tab. 7). Small PV light systems (10W panel, 7.2 Ah battery, 4 LEDs) have low investment costs (610 ZAR), reduce the electricity expenses and are simple to install and use.

Another solar option are water heaters. Solar geysers are implemented in social housing projects in South Africa. Because of the high investment costs (about 9600 ZAR), self-made water heaters from standard black pipe rolled to a coil and attached to a black wooden frame are a cheaper, yet effective option for heating water for cooking, washing and bathing.

Household-based plug-flow biodigesters with a fermenter volume of about $2m^3$ are deemed suitable to utilize currently unused organic household wastes, animal manures and grass. Up to $0,85m^3$ biogas per day can be produced, enough for cooking the staple meal *Umngqusho* (maize and beans). Field clearing with fire and, more important, firewood as main cooking fuel could be replaced, thereby reducing indoor-air pollution and deforestation. Additionally organic fertilizer is produced that can stimulate agricultural productivity and potentially increase food security. Another bioenergy option are *rocket stoves with sustainable forest management practices*. This implies a substitution of three-stone fires with a more efficient stove, while the biomass resource and collection is not changed. These stoves can be easily built from empty LPG cylinders. Sustainable management may aid conservation of natural forests and increase consciousness about the use of wood. Higher stove efficiency may decrease the time-consuming burden of firewood collection for women.

Additionally an *Integrated Terrace System*[2], suggested by the partner-NGO, complemented the list of proposed RET options.

The evaluation of these RETs with community members was not possible (IREPA-step 6 and consequently IREPA-step 7) due to their general lack of knowledge and understanding of RE. Hence, the AHP was performed by local key-informants (L. Boshier and D. Philips) and two authors of this paper (B.W., J.R.). Results of the AHP show that local social and environmental RET sustainability criteria such as access to clean water, soil, water and air protection, food security, gender-related aspects and social cohesion and stability were rated as more important than techno-economic criteria such as O&M and investment costs (Tab. 6).

The second AHP step revealed that an *Integrated Terrace System*, rocket stoves, solar water heaters or biodigesters, would be the most appropriate technologies for implementation (Tab. 7). All

[2] Aquaponic system for the organic production of tilapia (incl. feed), rice and vegetables with the aim of increasing food security and access to water for irrigation. Water is supplied by a ram-pump; fish faeces supplies plant nutrients.

RET options are simple, cheap and made from locally available resources. All RETs are suitable for installation at household level and tensions within the community and especially *mona* can be avoided when everyone is generally able to use the same RET. The rocket stove and the simple solar water heater have the highest benefit:cost ratio (Tab. 7) and are therefore deemed to be most beneficial for the households by the local key-informants (L. Boshier and D. Philips) and two authors of this paper (B.W., J.R.). However, these are not only economic benefits. Although the substitution of often unaffordable grid electricity may saves financial resources, e.g. to be used to purchase food to enhance food and nutrition security, the benefits additionally imply social and environmental factors. Implementation of these RETs would enable:

(i) to follow the intention of traditional leaders on showing innovative ways of using locally available materials and natural resources,

(ii) to educate and develop skills among community members in manufacturing, operation and maintenance, because a general lack of knowledge of RE among the community members was found to be the largest barrier to RET implementation,

(iii) to allow every community member to try and evaluate RET on an individual basis by keeping the risk associated with the introduction of new technologies low (Rogers, 1995).

4. Discussion

4.1. Centralized, top-down RE-policy in South Africa

To date RE policy instruments are the main driver of development in the RE sector (Negro et al., 2012; REN21, 2016; Resch et al., 2008). RE supporting policies frequently focus on and are often limited to the provision of fiscal incentives such as investment subsidies, provision of venture capital to support market introduction of RET, tax exemptions, emission regulations and feed-in tariffs (Gross et al., 2003; Negro et al., 2012). However, the lack of stable and properly aligned regional and local institutions is a key systemic problem in particular in countries of the South (Negro et al., 2012). Instability with regard to policy support, e.g. insecurity about energy tariffs, delayed issuing of power purchase agreements and conflicting messages from different government entities, is a major barrier for RE in South Africa (Pegels, 2011). Throughout Sub-Saharan Africa energy development projects show disillusioning success rates. Only 36% of the World Bank financed electric power projects were successful (Dunmade, 2002). In South Africa improvement of the coordination among policies and institutions is highlighted as prerequisite for effective RE implementation (Msimanga and Sebitosi, 2014).

Access to modern energy is perceived as important catalyst for economic growth and social equality (Pollet et al., 2015). Proposed bids for the REI4P are evaluated based on the requirements for *local content* (Msimanga and Sebitosi, 2014), the socio-economic development aims to be met (30%) and the energy generation price (70%) (Walwyn and Brent, 2015). So far South African companies have taken the lead in bidding consortiums, but considerable financial and technical back-up from international companies is involved (Msimanga and Sebitosi, 2014). *Local content* was claimed to be high in the bids, but actually technical equipment was not purchased from local manufacturers, although South African companies have implemented new construction facilities (Walwyn and Brent, 2015). Additionally, international energy experts and consultants are mostly not familiar with the historical context and show little interest in present-day challenges in South Africa (Msimanga and Sebitosi, 2014; Sihlongonyane, 2015). Consequently, the policy impacts of the REI4P on national economic growth and the inclusion of society are lagging behind expectations.

4.2. Transition towards participatory, bottom-up RE-technology selection

The limited focus of the REI4P on large-scale RE-supply at the lowest costs is a major barrier to national socio-economic development. Msimanga and Sebitosi (2014) call for a reform of the REI4P to include small and community-level projects (< 1 MW), which are currently excluded due to high up-front planning costs. The reform requires the inclusion of socio-cultural factors in the REI4P (Amigun et al., 2011, this study). The planning of small and communal RE-project needs to be based on the exploration and acknowledgement of diverse local land and natural resource management schemes, traditional community hierarchies (Hamann and Tuinder, 2012; this study) and the role of energy in people’s lives (Kaygusuz, 2011; this study).

Small and community level RE-projects may stimulate the energy-transition from bottom-up, in addition to the political commitment for the societal transformation towards a green economy in South Africa (DEA, 2011). RET-niches and a dedicated policy framework can reinforce each other to accelerate system innovation towards RE (Geels, 2005).

However, as revealed by this study and supported by Amigun et al. (2011), it is the lack of knowledge and understanding of RE that poses a major barrier to RET implementation in the rural Eastern Cape. This needs to be addressed by adequate communication strategies that disseminate information about climate change and the consequent energy-transition towards a low-carbon energy system (DEA, 2011; Pegels, 2011). Small and communal projects, initiated through a reformed REI4P and implemented at communal level, for example as public-private partnerships (Sovacool, 2013), provide suitable spaces for learning processes about RET characteristics, integrated food and RE agricultural systems, the role of energy in people's lives and household energy demand (quantity and quality) (Geels, 2005).

For project planning and implementation, it is suggested to include IREPA into the REI4P. IREPA provides a common methodology for RET assessment and appropriate technology selection at local level that aids comparability and systematic knowledge accumulation to accelerate decentralised RE production in South Africa (Smith et al., 2010).

4.3. Evaluation of IREPA based on case study research

The case-study research evaluated whether the IREPA methodology is suitable for the exploration of locally relevant factors for appropriate RET selection in rural smallholder farming systems. Access to and trust within the local community is regarded as a crucial prerequisite for a participatory bottom-up approach (IREPA step 1) (Wüstenhagen, 2007). This was ensured in our research through the existing relationship between the partner NGO and the local chief, who had approached the NGO to assist them in utilizing existing natural resources efficiently and sustainably. This provided a favourable setting for our research. PLA methods actively engaged the local population in the research process. Relevant factors characterising local livelihoods, in particular with respect to the role of energy in people's lives were identified (IREPA step 3). These factors, transcribed into local

RET sustainability criteria, were used to assess the ThREP, the GREP and the TREP (IREPA step 2 and 4a/b). Data on RR, which were sufficiently available from statistical databases, were paired with household and community data, enabling the pre-selection and planning of RET options (IREPA step 5).

However, the community members were not able to participate in the AHP. The rating of criteria and RET options based on pair-wise comparisons was found to be too abstract, as this requires a sufficient knowledge level about RET (IREPA step 6 and 7). Consequently, key-informants took part in the ranking exercise. To account for such situations, Barry et al. (2011) suggest workshops with practical RET show cases for RE knowledge dissemination. Incorporating a practical workshop in IREPA after step 5 could provide community members with sufficient information on RET to participate in the decision-making process. Further, to enable participation of community members in decision-making, the AHP could be adapted by categorising the RET sustainability criteria into thematic clusters. This would reduce the number of pairwise comparisons, decrease complexity when participants only compare criteria of similar topics and thus increase accuracy of results (Brugha, 1998). Another option for enhanced participation is the straight-forward MCDA method Simple Multi-Attribute Rating Technique (SMART) (Chen et al., 2011). However, it has to be considered that not all community members might be able to participate, for example women, due to a male-dominated society; younger men and women due to social hierarchies and poorer community members due to lower social status (Lemke and Bellows, 2016).

For practical and sustainable RET implementation after IREPA, “early adopters” should be identified in the community. Due to their higher socio-economic status they are better able to take the risk associated with new technologies (Rogers 1995). For the identification of early adopters, IREPA should include questions in the household survey to explore socio-demographic and economic characteristics, allowing for household stratification.

5. Conclusions

IREPA was developed as a participatory, bottom-up approach for appropriate RET selection and REIP assessment for RE project planning in smallholder farming systems to facilitate RE implementation in rural areas.

Current REPA methodologies lack a connection to the role of energy in people's lives. RE implementation is so far mainly driven by top-down policy instruments that are often limited to the provision of financial incentives (Negro et al., 2012). To encourage the implementation of RET a shift from top-down initiatives to bottom-up approaches is required. In case of South Africa the participatory, bottom-up perspective could enrich the REI4P to strengthen rural development. Prior to any rural RET implementation a participatory REPA including educational aspects such as IREPA should be performed. As the application of IREPA requires time and greatly benefits from transdisciplinary research, it is recommended that government institutions and development agencies collaborate with interdisciplinary research centres and dedicate sufficient financial resources to project planning.

IREPA ideally involves the local population in a mutual knowledge exchange and educational process for REIP assessment as part of RE project planning. In this way, IREPA explores locally relevant social, institutional, environmental and techno-economic factors which are subsequently employed in a participatory decision-making process for the selection of locally appropriate RET. The adaptions recommended by this research would render IREPA a suitable bottom-up approach for the assessment and effective implementation of RET, stimulating socio-economic development in rural areas.

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